NUMERICAL SIMULATION OF PARALLEL ROBOTS WITH DECOUPLED MOTIONS AND COMPLEX STRUCTURE IN A MODULAR DESIGN APPROACH

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Abstract:

In this paper, a modular design methodology is proposed for numerical simulation of parallel robots. Static stiffness is a mechanical characteristic that describes the behaviour of a structure under static force in terms of elastic deflection and can be evaluated for robotic manipulators by means of Finite Element Method numerical simulation. Many parallel robots have multiple identical legs that can be considered as multiple instances of a unique sub-assembly. On this base, we present an efficient approach to perform numerical simulation of these robots. In addition, an application case to the Isoglide family of parallel robots is presented to show the effectiveness of this approach. A new rhombic leg structure is also compared with a classical leg structure. Compliance maps for the Isoglide3-T3 robot with rhombic legs are also provided. Finally, structural symmetry of the geometrical model of the robot is used to find symmetries in the compliance maps and to check calculation correctness.

Keywords: parallel robot, stiffness, symmetry, FEM, modular design

1 Introduction

With the development of advanced robotic technology, mechanical design methods have been extensively studied to create new parallel mechanical systems with specified architecture and number of degrees of freedom (DoF). Original applications for parallel machine tools and parallel kinematics machines have been very recently proposed. They have been applied in various fields such as manufacturing simulators [1-2], micro robots, industrial high speed pick and place robots [3], medical robots [4]. Parallel mechanisms have become more and more popular because they have better properties, such as high load/weight ratio, velocity, stiffness, precision and low inertia. It is believed that parallel robot mechanisms with few DoFs, usually two to five, are especially prospective because of their simpler structures and lower production costs [5-6].

Parallel robotic manipulators with decoupled motions and various degrees of mobility have been recently proposed [1-2]. Figure 1-a presents an example of a 4-DoF parallel mechanism whose end effector, called platform, can achieve four independent motions: three orthogonal translational motions and one rotational motion with respect to the fixed base [2].

This manipulator called Isoglide4-T3R1 was designed and implemented by LaMI in a modular approach. The work presented in this paper is applied to translational parallel manipulator Isoglide3-T3 (Figure 1-b) but it could be extended to other solutions of the Isoglide robot family including Isoglide4-T3R1.

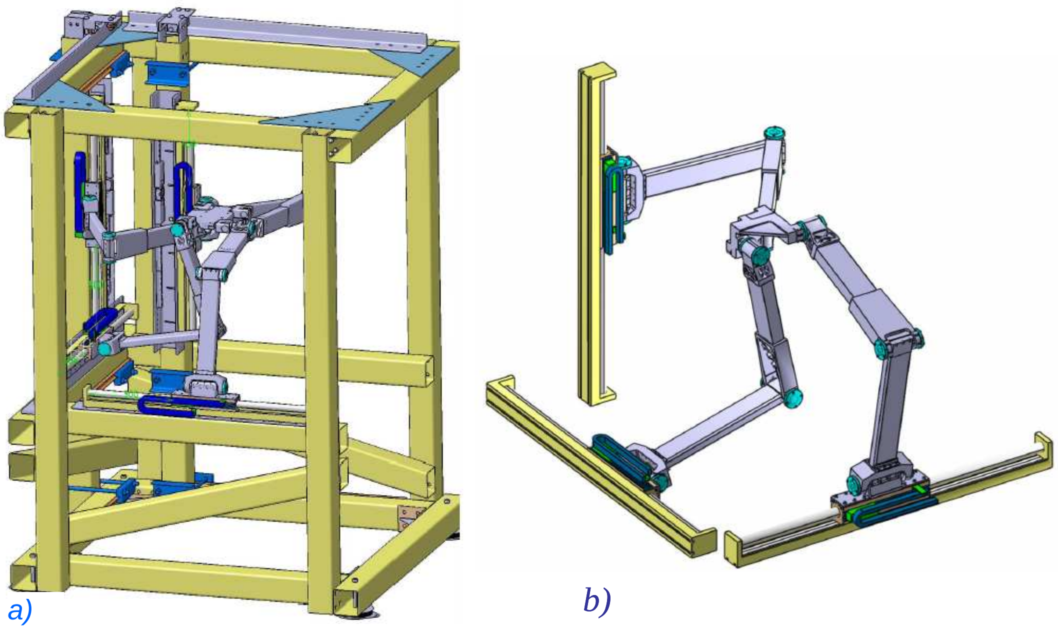


Figure 1. CAD model of two robots from Isoglide family: a)Isoglide4-T3R1 & b)Isoglide3-T3.

2 Problem setting

2.1 Stiffness analysis

The design of parallel mechanisms is usually based on the use of evaluation criteria involving workspace, dexterity, payload, global conditioning index, and stiffness [7]. Among these properties of mechanical systems, stiffness is a particularly important characteristic for robot specification. In addition, characterizing parallel architectures for practical applications requires evaluating their stiffness. This can be useful for developing analytical design criteria and improving properly prototype performance as proposed for examples in [8-10].

A great deal of work has been done on stiffness analysis of parallel mechanical systems and it has direct application in industry. The methods reported in the literature [3,8-11] can be classified into structural analysis by Finite Element Method (FEM) and Jacobian matrix method. The first method [3,8-9] is based on an approximation of the original model by a discrete model made of elements and nodes, leading to the stiffness matrix that is dependent on the nature of elements in the structure. The second method is based on the Jacobian matrix that is used to form a generalized stiffness matrix [11]. Significant examples of stiffness analysis on robots can be found in [8-11]. This paper will mainly focus on numerical simulation for the structural analysis method.

2.2 FEM Modelling

Most of the FEM software offer two ways of creating models:

- The first one is the direct *Graphic User Interface (GUI) method*, using a point and click strategy and interactive control on the model.

- The second one is much closer to programming and will be called *scripting method*. Most software include a programming language with basic structures (sequence, test and loop), variable parameters and sub-functions.

Despite its advantage of intuitiveness, the GUI method is not efficient for the numerical simulation of parallel robots. First, for a complex mechanical system, the FEM model is very time consuming. For developing a complex model, it is common to dispatch the developing process on several people that are geographically far one from each other and do not work synchronously. This is what we call the 'distributed method'. The GUI methodology is mainly an individual way of creating models and the distributed method can not be applied easily in this case. Second, the GUI method itself is not a formal, ordered and systematic method. A same model can be created via many different ways. It is based on a point and click strategy. The errors can not be examined and modified easily. Third, in the preliminary design phase of a product, we often need to explore the design space and generate many different alternatives to choose the best one. For parallel robot design, this means building assemblies of standard and reusable components. This is not easily achieved with GUI methodology.

In the process of evaluating the stiffness of Isoglide robot family, we study the stiffness of a parallel robotic manipulator with three isotropic translational motions (Isoglide3-T3) [1]. Figure 2 represents a classical serial leg structure, while Figure 3 represents a rhombic structure, where each leg is a parallel mechanism in itself made of two sub-chains. With the GUI method, it is difficult to make use of the results obtained by solving the classical structure (Figure 2) while we try to study the rhombic structure (Figure 3), let alone the comparison of different solutions. Without reusability and exchangeability, which are some of the fundamental concepts first introduced with Object Oriented Programming [12], GUI method is proved to be unsuitable and cannot meet the demand of numerical simulation.

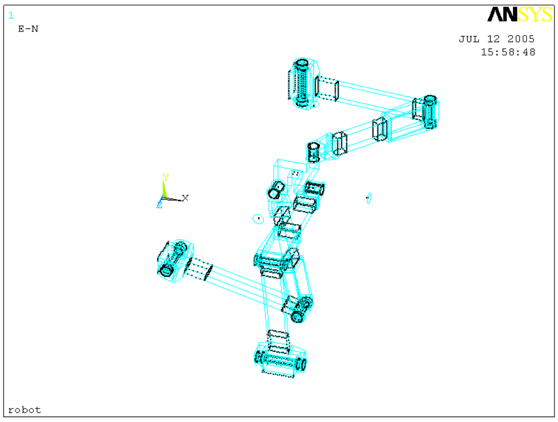


Figure 2. Leg in classical structure.

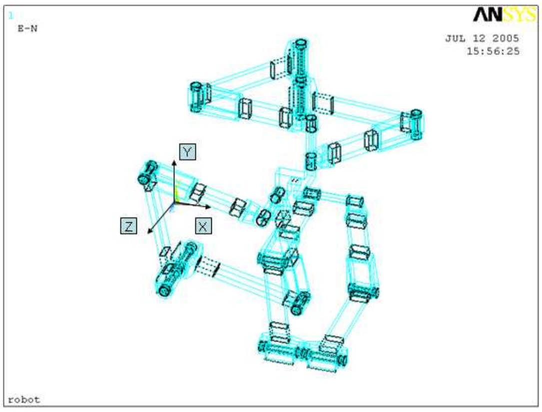


Figure 3. Leg in rhombic structure.

3 Modular design for FEM numerical simulations

3.1 Modular design

It is worth noting that almost all parallel robotic manipulators are characterized by their symmetry in structure. The idea of modular design can help us in the FEM numerical simulation of parallel mechanisms. A module is an assembly of parts that can be integrated or repeated several times in the structure of a machine. Modular design takes advantage of repeating patterns and hierarchical relations in the assembly structure of a machine or a mechanism. In fact, modular products are products that fulfill various functions through the combination of distinct modules [13-15]. The modular design of products leads to a large number of different products by creating distinct combinations of modules and components. This can give each product distinctive functionality, features, and performance levels [15-17]. The design of modular products is of considerable importance in enabling companies to respond rapidly to changes in the market environment. Examples of this type of modularity can be found in automobile industry and computer industry. The modular approach promises the benefits of computability, reusability, exchangeability and improved communication.

On the base of the concepts of modular product design and substructuring, this paper develops a modular design approach to simulate numerically complex parallel mechanical systems.

3.2 Functional analysis and assembly decomposition

A typical FEM simulation is generally divided into three steps, which are respectively model building, load application and solving. With the idea of modular design, we can deal with the three steps in a particular way. Indeed, a FEM model consists of geometrical model and physical model. It is suitable to arrange the building of model into a hierarchical decomposition made of sub-assemblies and components, while leaving behind load application and solving to later steps. In this way, the whole FEM model is modularized functionally. In addition, the FEM model can be modularized physically and geometrically. For example, in a structure with repeated patterns (such as the three legs of a parallel robotic manipulator), we can generate one module to represent the pattern and simply make copies of it at different locations, thereby saving a significant amount of computer time. Considering mainly from the function, computability, reusability and exchangeability of module, we can decompose and disassemble the FEM model into modules. The assembly FEM representation of parallel robot Isoglide3-T3 is shown in Figure 4; disassembling process is shown in Figure 5. A leg can be disassembled into ten modules. Considering symmetry of structure, number of modules of Isoglide3-T3 comes to thirty-one (three legs together with a platform).

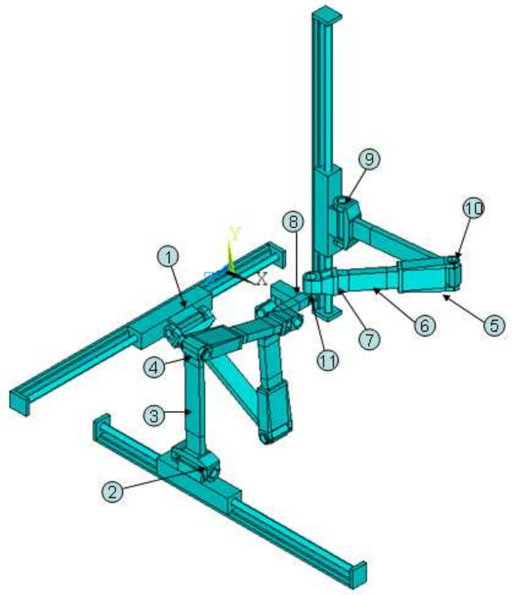


Figure 4. FEM model of Isoglide3-T3 assembly.

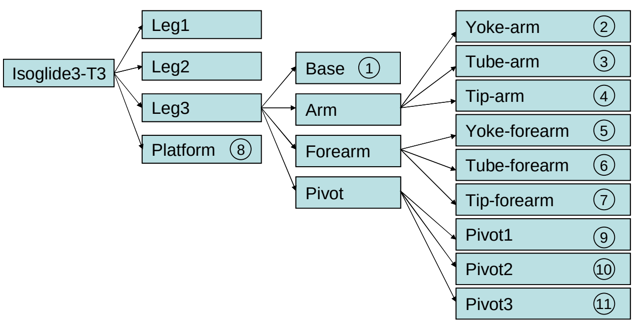


Figure 5. Disassembling Isoglide3-T3 model into sub-assemblies and components.

3.3 Substructuring

This step concerns mainly the creation of model for module, which is based on the concept of substructure. In ANSYS® software, the substructure analysis is defined as “a procedure that condenses a group of finite elements into one element represented as a matrix. The single-matrix element is called a superelement” [17-18]. Indeed, the only difference is that the superelement is created first as a module by performing a substructure generation analysis. Modularization and substructuring reduce computing time and allow solving very complex problems with limited computer resources. Nonlinear analyses of structures containing repeated geometrical patterns are typical problems where substructuring can be employed.

APDL, which stands for ANSYS Parametric Design Language, is a suitable candidate for module design to FEM simulation. It is a scripting language that you can use to automate common tasks or even build your model in terms of parameters (variables). APDL also encompasses a wide range of other features such as repeating a command, macros, if-then else branching, do-loops, and scalar, vector or matrix operations.

With APDL, design is completely formal and systematic. A typical module is realized by the following steps:

- Building geometrical model.
- Defining element type, material property and associating element attributes with geometrical model.
- Specifying the analysis type, the type of equation solver, etc.
- Generating superelement equivalent to the considered module (condensing finite elements into one superelement).

The result of modular analysis is a superelement matrix that can be copied at different locations, according to the FEM simulation requirement.

3.4 Assembling modules and solving

With all of modules and components available, global model is assembled by importing all superelement matrix files into an assembly file. The assembly file is particular because it concerns only the assembly of modules. It combines all the separate modules into the final global model and generates the solution of model. By modifying this file, numerous combinations of modules can be created. It consists of the following steps:

- Defining a global coordinate system and some local coordinate systems.
- Assembling all modules.
- Applying loads. In ANSYS, this terminology includes boundary conditions and externally or internally applied forces.
- Solving the complete problem.

For instance, the substructure of Tip-forearm and its assembly is shown in Figure 6. With ANSYS, the first step is to create and locate the superelements in global model (SETRAN command). The second step is to import the superelement data that were previously calculated in generation pass (SE command). Loading and solving are encompassed in this step.

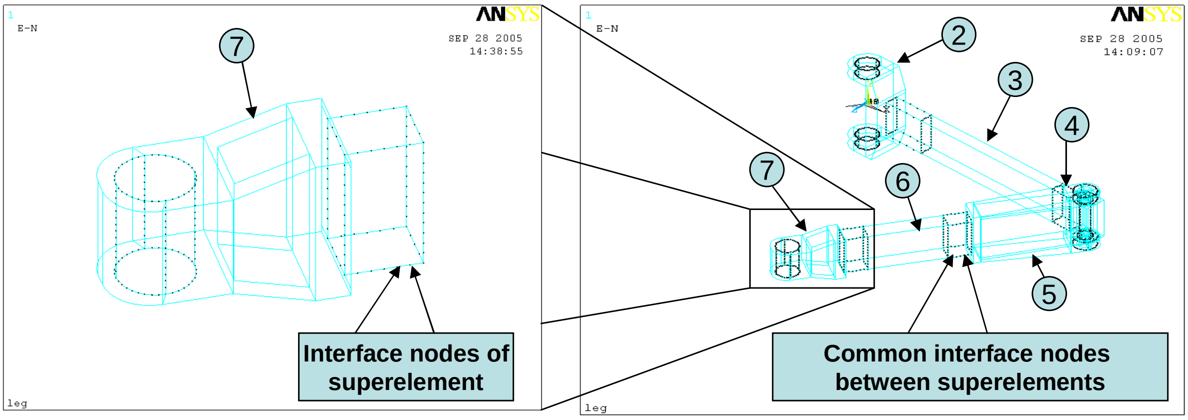


Figure 6. Sub-structure Tip-forearm and its assembly.

By defining the master DoF between interfaces of contacting modules, the main advantage of a modular design-reusability and exchangeability can be guaranteed. It means that one or more modules can be easily replaced provided the interfaces remain with the same specification.

4 Application to Isoglide robot family

4.1 Theoretical base for numerical simulation

Generally, a stiffness evaluation can be represented by stiffness matrix $[K]$ which can be obtained by computing displacements $\overrightarrow{dp}$ and rotation angles , occurring on platform at a static configuration when a force $\vec{F}=(F_x, \quad F_y, \quad F_z)$ and a moment $\vec{M}=(T_x, \quad T_y, \quad T_z)$ act upon it. The stiffness $[K]$ can be formulated as (1):

$$\begin{bmatrix} \vec{F} \\ \vec{M} \end{bmatrix} = \begin{bmatrix} K_{Fp} & K_{F\theta} \\ K_{Mp} & K_{M\theta} \end{bmatrix} \begin{bmatrix} \overrightarrow{dp} \\ \overrightarrow{d\theta} \end{bmatrix} \quad (1)$$

To calculate the compliance matrix, stiffness equation (1) can be transformed into compliance equation (2):

$$\begin{bmatrix} \overrightarrow{dp} \\ \overrightarrow{d\theta} \end{bmatrix} = \begin{bmatrix} S_{pF} & S_{pM} \\ S_{\theta F} & S_{\theta M} \end{bmatrix} \begin{bmatrix} \vec{F} \\ \vec{M} \end{bmatrix} = \begin{bmatrix} K_{Fp} & K_{F\theta} \\ K_{Mp} & K_{M\theta} \end{bmatrix}^{-1} \begin{bmatrix} \vec{F} \\ \vec{M} \end{bmatrix} \quad (2)$$

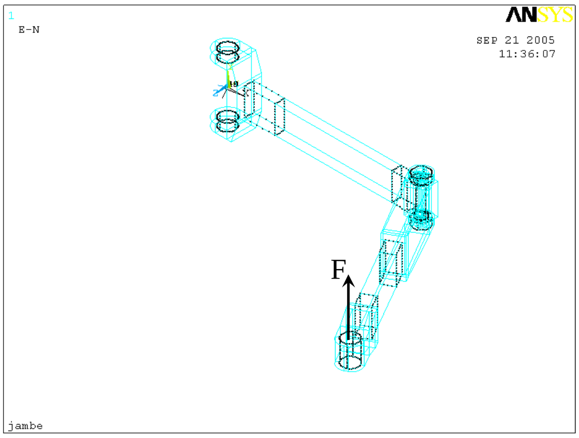
By numerical simulation, we can determine the compliance matrix. For example, for sub block S_{pF}:

$$S_{pF} = \begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{bmatrix} \quad (3)$$

The value S_{ij} can be determined and the compliance map can be calculated.

4.2 Compared behaviour for two types of legs of Isoglide robot family

First stiffness studies of Isoglide4-T3R1 were performed in [19, 20]. In this work, a modular design approach is used and several solutions are compared. Two possible structures are considered for legs in Isoglide robot family. Figure 7 shows a FEM model of leg in classical structure, while Figure 8 represents a FEM model of leg in rhombic structure. Making use of the substructures available, we have created the leg FEM model as shown in Figure 8. It is interesting to compare the compliance of two solutions, which can help us to optimize design. Figure 9 is the graph of compared deflections under an unitary force F.



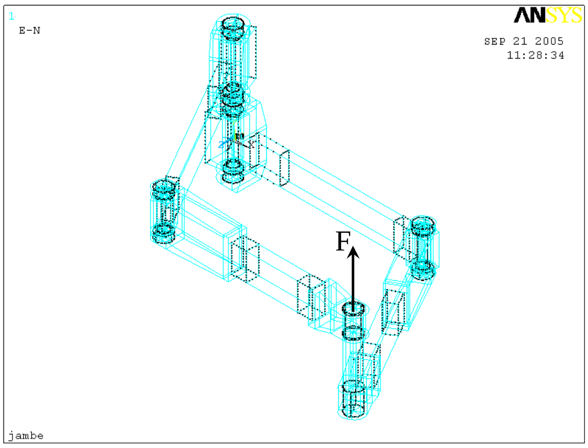


Figure 7. Leg in classical structure. *Figure 8. Leg in rhombic structure.*

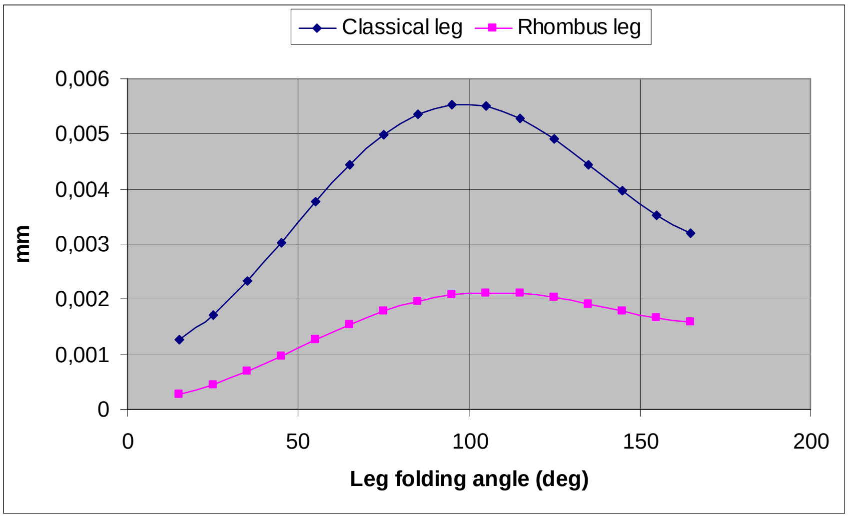


Figure 9. Graph of compared deflections of classical and rhombic legs.

Several conclusions can be obtained from Figure 9. First, for both types of legs, deflection varies a lot with respect to the folding angle in a 1 to 5 ratio. Deflection is minimal when the leg is folded and subject mainly to flexion. There is also a local minimum in the unfolded position. Both legs reach their maximum deflection when angle approaches 95 degrees because of torsion moment, which causes the biggest part of deflection. Second, the leg in rhombic structure is greatly reinforced relatively to the classical one. A rhombic leg is geometrically equivalent to two classical legs but is more than two times stiffer.

4.3 Compliance maps of a robot of Isoglide family

Following results are for Isoglide3-T3 robot with rhombic legs presented in Figure 10. On the base of equation (3), the value S_{ij} can be determined by calculating the displacement p_i and using $S_{ij} = p_i / F_j$ with unitary force F_j. Figure 10 shows the example of the displacement

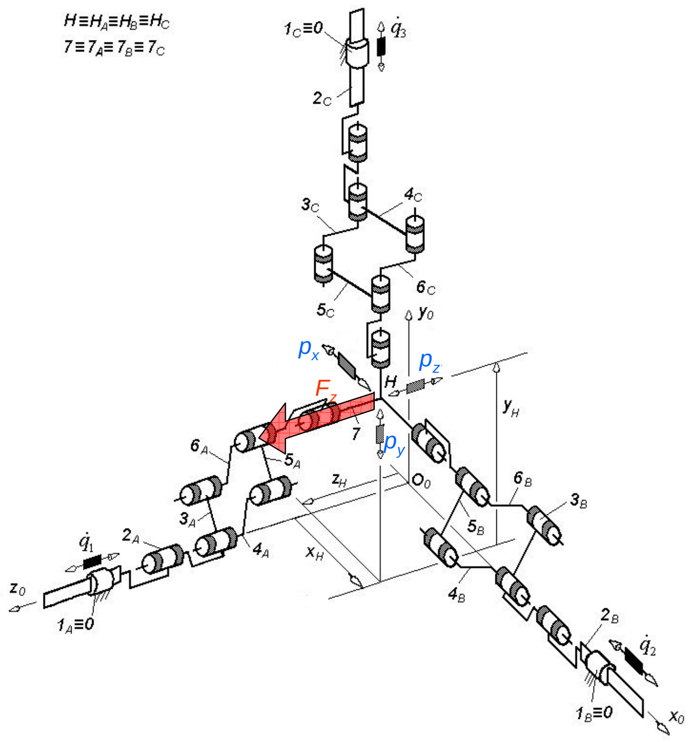


Fig 10. Kinematic diagram of rhombic Isoglide3-T3.

response p_x, p_y, p_z of the robot to a unitary force F_x. The whole series of compliance maps are shown in Figures 11-15. They will help diagnose structural behaviour of this robot around the full workspace.

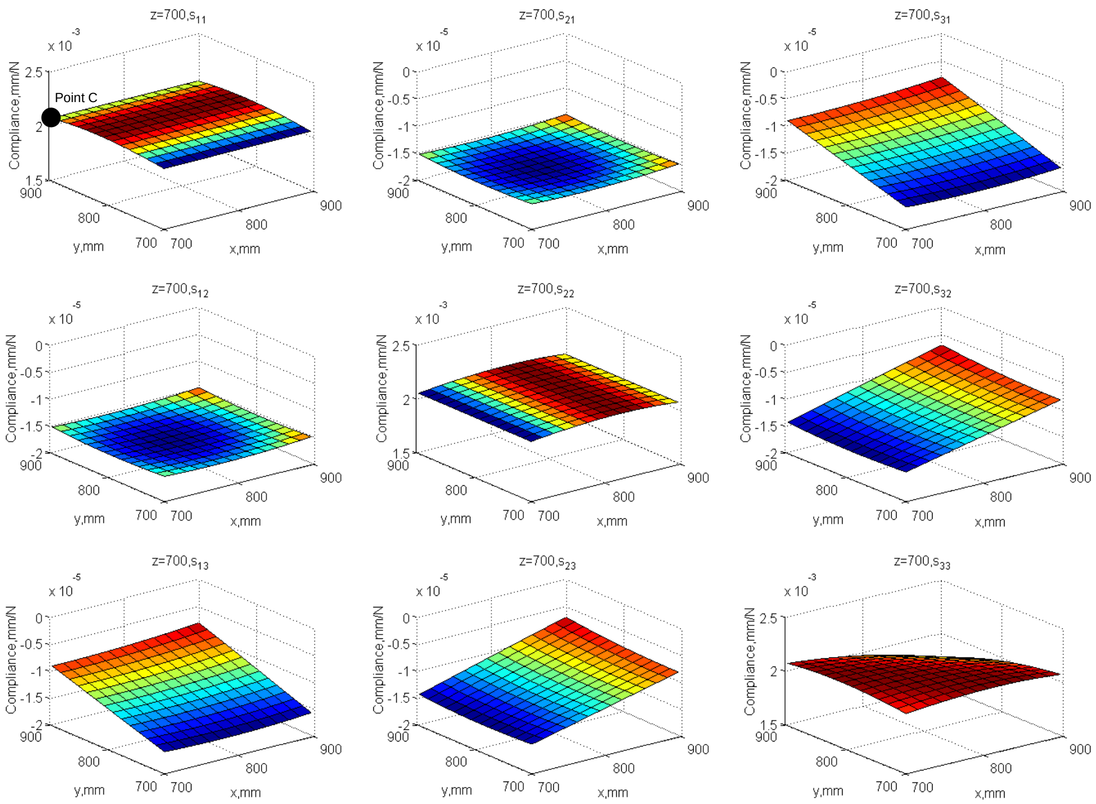


Figure11. Compliance map, z=700mm

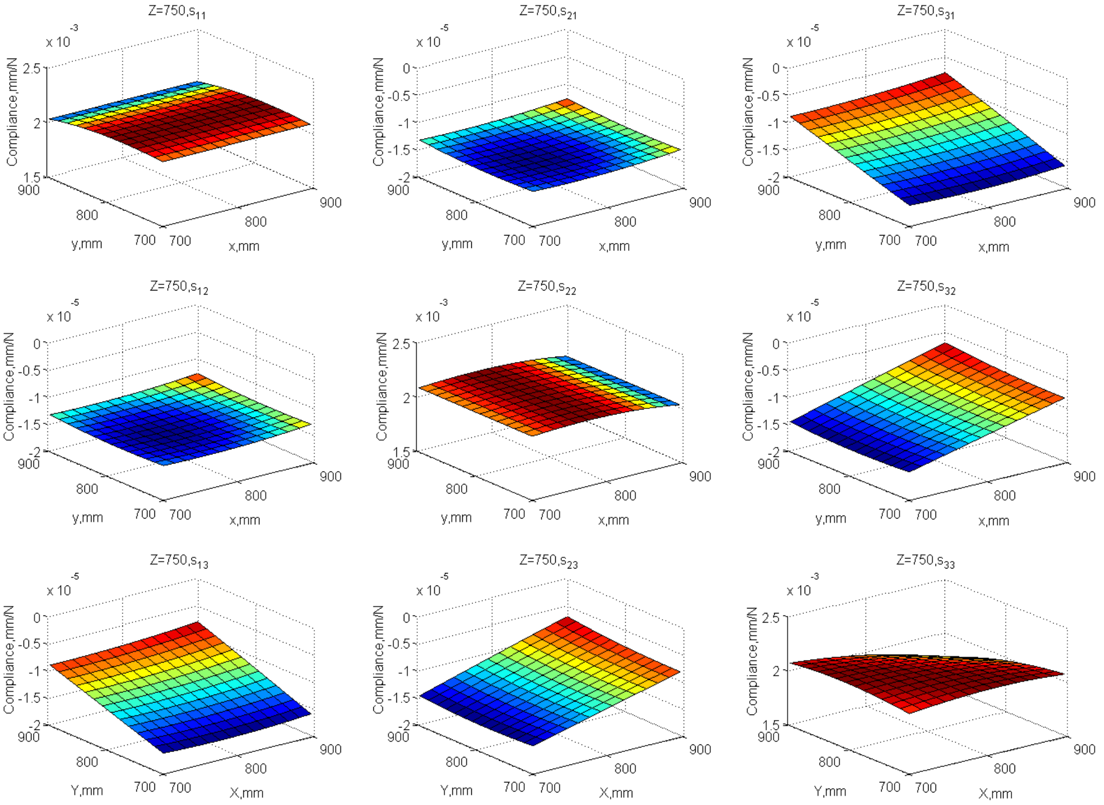


Figure 12. Compliance map, z=750mm.

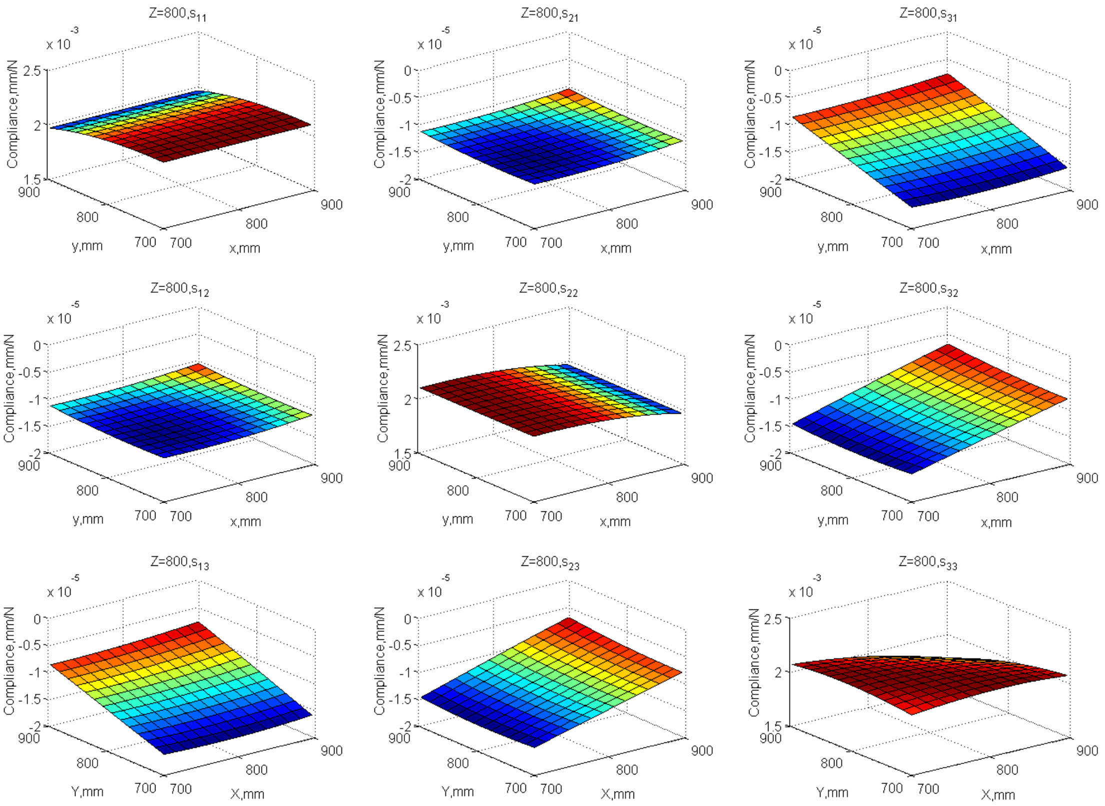


Figure 13. Compliance map, z=800mm

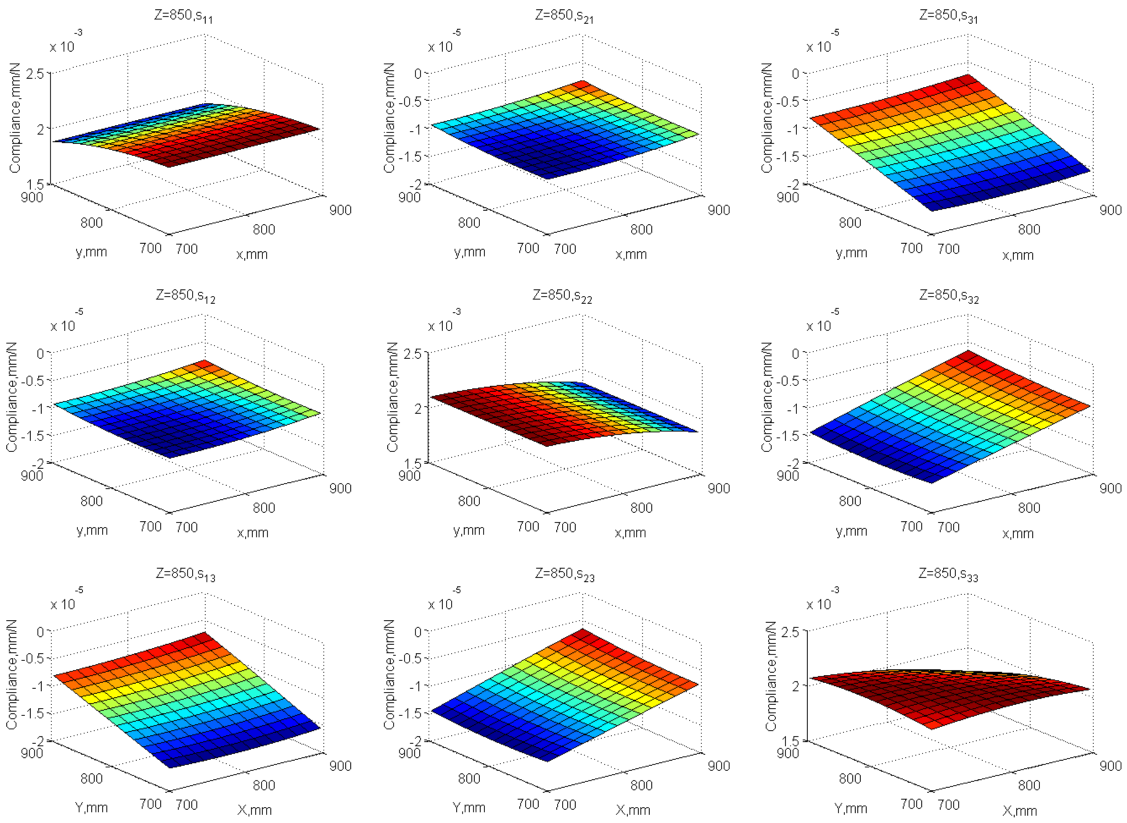


Figure 14. Compliance map, z=850mm

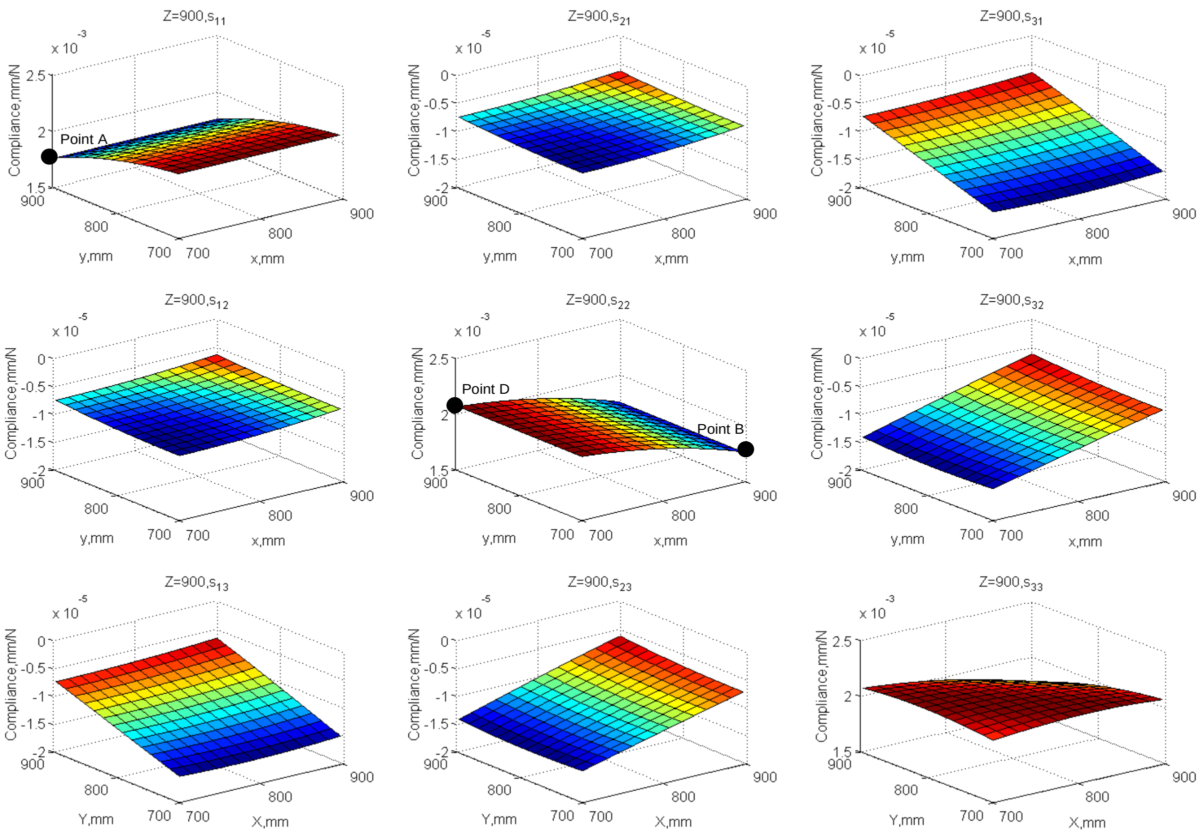


Figure 15. Compliance map, z=900mm

The compliance maps ranging from vertical coordinate Z=700 mm to Z=900 mm are respectively shown in Figure 11-15. From these figures, we can see that compliance ranges from 2 10^{-5} mm/N to 2.5 10^{-3} mm/N.

If vertical coordinate Y is a constant, for example in Figure 11 where Z=700 mm, the values of diagonal terms (S_{11}, S_{22}, S_{33}) are much greater than non-diagonal terms Sij ($i \neq j$) S_{11} remains constant along the X axis, S_{22} remains constant along the Y axis; S_{33} evolves with same tendency along axes X and Y.

Comparing Figure 11-Figure 15, we can see that side Y=900 of surface S_{11} decreases from 2.1 10^{-3} mm/N to 1.75 10^{-3} mm/N. The opposite side of the S_{11} surface (Y=700) does not change. The evolution of S_{11} is independent on X. It can also be seen in Figure 11 that a unitary force F_x applied in the X direction on the points of axis $Y \approx 800\ mm$ will generate maximal robot displacement in the X direction. Compliance S_{22} has the same behaviour as S_{11} if the X and Y axes are swapped. Concerning S_{33}, it does not change much from Figure 11-Figure 15 and its maximal value is 2.1 10^{-3} mm/N.

The Isoglide3-T3 robot has a very special symmetrical design. It has strong consequences on the shape of compliance maps. Two types of symmetries can be observed. The first one is a triple symmetry that can be observed on every point of the diagonal of the cubic workspace (axis defined by $X = Y = Z$). In Figure 11, when $X = Y = Z = 700\ mm$ or in Figure 15, when $X = Y = Z = 900\ mm$, it can be checked that $S_{11} = S_{22} = S_{33}$. According to the definition of compliance, this means that on this point, if we apply a unitary force F in X, Y or Z direction, the robot will generate the same displacements in X, Y and Z direction respectively. As the FEM model was defined without gravity, it is normal to find here a statically isotropic behaviour. The second one is a double symmetry. For example, in Figure 15, we can see that S_{11} on point *A (700, 900, 900)* and S_{22} on point *B (900, 700, 900)* are equal to the same value of 1.75 10^{-3} *mm/N*. Another example would be S_{11} on point *C (900, 900, 700)* Fig. 11 and S_{22} on point *D (700, 900, 900)* Fig. 15: the values are the same and equal to 2.1 10^{-3} *mm/N*. This is another form of the structural symmetry. From all of these comparisons we can verify the correctness of results.

5 Conclusion

In this article, a modular design approach is presented to simulate the compliance of parallel robots with decoupled motions and complex structure. The use of modular design approach offers several important advantages. First, it is well suited to parallel robots with several identical legs that are modelled as sub-assemblies. Legs are calculated once and used several times. Each FEM model of sub-assembly or module is simple and can be examined, checked, corrected and modified easily. For each module, ANSYS Parametric Design Language is used to develop the program in an object oriented approach. In this way, the distributed policy can be applied and a complex model can be decomposed and solved by several persons. Furthermore, by parameterization and substructuring, the size of the FEM problem is controlled and problem solving is accelerated. With modular design methodology and substructuring, every numerical simulation results are obtained by only re-assembling existing modules. It should be noted that our modular design approach is not limited to parallel robots but is also suitable for every type of machine with a repeating pattern.

The effectiveness of this approach was demonstrated on Isoglide3-T3 robot and some advantages were revealed, especially in the comparative study of different solutions. Two solutions based on classical and rhombic leg structure were tested. The rhombic solution proved to be more than two times stiffer than the classical one. Compliance maps were also computed for the complete rhombic Isoglide3-T3 robot. Triple and double symmetries in compliance maps could be noticed, which is due to the very special symmetrical geometry of Isoglide3-T3. This was used to check calculation correctness. This modular approach can be applied not only in the conceptual design phase but in detailed design as well.

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